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The Concept of New-Generation Steam Turbines for the Coal Power Engineering of Russia. Part 2. Substantiating the Long-Term Strength of the Steam Turbine's High-Temperature Rotors

A. G. Kostyuk, V. G. Gribin, and A. D. Trukhnii
Moscow Power Engineering Institute, ul. Krasnokazarmennaya 14, Moscow, 111250 Russia

Abstract—The possibility of constructing a K-660-30 two-cylinder steam turbine for ultrasupercritical steam conditions with reheating, the concept of which was described in the first part of this paper, is substantiated. It is shown that this turbine can be constructed using the available heat-resistant materials.

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Ensuring long-term strength of the high-temperature elements used in a steam turbine is a factor of crucial importance in mastering the construction of power units for ultrasupercritical parameters. Among the problems that have to be solved for constructing such power units are selection (or development) of materials for making high-temperature rotors and shells, and working out suitable design solutions aimed at decreasing the temperature of these components.

Below, these two aspects are considered as applied to the high- and intermediate-pressure rotor (HIPR) used in the combined high- and intermediate-pressure cylinder (HIPC).

A shift from the standard temperatures of live and secondary superheated (reheat) steam $t_0/t_{\mathrm{r.s}}$ = 540/540°C typically used in power units for supercritical steam conditions to the temperatures $t_0/t_{\mathrm{r.s}}$ = 610/620°C that are adopted in the considered project can be made only with the use of medium-alloy steels with a chromium content from 9 to 12%. Outside of Russia, rotor steels with such content of chromium have long been widely used to make high- and intermediate-pressure rotors for supercritical-pressure turbines (see, for example, [1]). In our opinion, Grade HR1200 (11CrMoWCoVNbB) Japanese steel [2] and Grade EI993 (18Kh12VMBFR) Russian steel are the most suitable steels for making rotors intended to operate with a metal temperature of around 600°C. This opinion is in line with the conclusions drawn in [3].

The main characteristics of Grade EI993 steel are given in [4], and some information on it can be found in [3]. In [4], EI993 steel is referred to as a steel for making rotor blades, and in [3] it is recommended as a material for making high-temperature rotors.

The long-term strength characteristics of the recommended steels, as well as those of Grade EI756 (Kh12V2MF) steel (for comparison) are given in Table 1.

In its chemical composition the Japanese steel HR1200 is close to the Russian EI993 steel, but the long-term strength characteristics of HR1200 steel are noticeably better than those of EI993 steel, which is in all likelihood due to a more advanced technology of manufacture, which makes it possible to obtain higher purity of metal.

The long-term strength of the HIPR used in the turbine for ultrasupercritical steam conditions is analyzed for the case of using the Russian EI993 steel.

The list of data given in Table 1 is insufficient for estimating long-term strength; creep characteristics must also be known in addition to these data, because it is only these parameters using which it is possible to establish regularities according to which stresses vary with time in the dangerous zones of a rotor. The safety margins are calculated using the procedure described in [5, 6] and the appropriate computer program.

The constants appearing in the creep law at constant stress and temperature must serve as initial data on the properties of material

$$\varepsilon^{\mathrm{cr}} = A\sigma^n\Omega(t); \quad \Omega(t) = t + a(1 - \mathrm{e}^{-pt}),$$

where σ is the stress, MPa; $\varepsilon^{\mathrm{cr}}$ is the relative creep deformation, t is time, h; and A, n, a, and p are constants.

The values of the characteristics given in Table 2 were obtained from processing a limited set of data on

Table 1. Long-term strength $\sigma_{\mathrm{l.t.s}}$ (MPa) of chromium rotor steels (100000 h, data of [3])

Steel	Temperature, °C			
	560	600	620	650
EI756(Kh12V2MF)	150	120	–	–
EI993 (18Kh12VMBFR)	220	170	110	–
HR1200(11CrMoWCoVNbB)	300	210	170	100

the EI993 steel [3, 4]. The parameters A and n are the most important ones of them.

Figure 1 shows a sketch of the HIPC's fragment located in the first-stage zone of the high-pressure part (HPP). The long-term strength of the fragment is analyzed for the metal temperature equal to 600°C.

The high-pressure rotor (HPR) contains the following potentially dangerous zones:

A—the fillet of the T-shaped root joint,

B—the disk fillet, and

C—the surface of the central channel.

In the subsequent, the long-term strength safety margin $n_{\text{l.t.s}}$ was determined from the following dependence:

$$n_{\text{l.t.s}} = \sigma_{\text{l.t.s}}/\sigma_{\text{eq}},$$

where $\sigma_{\text{l.t.s}}$ is the long-term strength for the 50% probability of fracture at a service life of 200000 h and the corresponding temperature of metal, and σ_{eq} is the maximal equivalent stress calculated taking into account the influence of stress concentration in the zones A and B.

The safety margins for the zones B and C were calculated using a computer program the algorithm of which is based on the procedure described in [5, 6]. Three calculation cases were carried out: VD1, VD2, and VD3. All three cases were carried out for the same temperature of metal equal to 600°C and for the same creep characteristics (Table 2) and long-term strength $\sigma_{\text{l.t.s}}^{200} = 160$ MPa on the basis of 200000 h of operation. The calculation results are given in Table 3.

The versions VD1 and VD3 differ from each other only in the shaft size. Increasing the shaft radius from 0.30 to 0.35 m results in that the safety margin becomes noticeably smaller, but its values remain a fortiori high and are essentially higher than the permissible values, which lie, according to different estimates, in the range $n_{\text{perm}} = 1.3–1.6$. In all likelihood, the values $n_{\text{l.t.s}} \geq 1.3$ can be considered permissible for the zones B and C. The safety margins in Table 3 are calculated in accordance with the two creep hypotheses: ageing and yield. It can be considered that these two values give the upper (the yield hypothesis) and lower (the ageing hypothesis) estimates of safety margins.

Thus, the long-term strength safety margins obtained in the zones B and C for the rated operating mode of the turbine are noticeably higher than their permissible values; hence, the long-term strength is ensured.

The VD2 version was calculated conditionally assuming that that half of nominal steam flowrate was passed through the turbine. It was supposed that steam flowrate was controlled at variable pressure and constant temperature. In view of this, it is considered that the steam pressure in the first disk zone and the axial tensile force are halved when half of nominal steam flowrate is passed. It can be seen that the long-term strength safety margins on the channel surface decrease significantly (by more than a factor of 1.5), whereas the safety margins on the fillet surface decrease only slightly: by 4–6%. Nonetheless, even under these a fortiori worsened conditions the safety margins for the zones B and C in the HIPR should be considered as quite permissible.

Table 2. Creep characteristics and long-term strength of Grade EI993 steel (200000 h)

Temperature, °C	A	n	a, h	p, h^{-1}	$\sigma_{\text{l.t.s}}$, MPa	b*
560	7.800×10^{-19}	6	10000	0.0032	210	14
600	1.087×10^{-19}	6	3200	0.0032	160	10.9

* Estimated values of the parameter b in the long-term strength law $t_{\text{fr}} = B\sigma^{-b}$, where t_{fr} is the time to sample fracture at the stress σ, and B is a constant.

As was already noted, the region A on the inner surface of the disk rim fillet (see Fig. 1) is also a dangerous zone. The long-term strength safety margins for this region were calculated using the procedure suggested in [7] for the standard tail of a T-shaped joint according to OST (Industry Standard) 108.260.06-84 [8] with making some changes to the geometrical characteristics. The main dimensions of the root joint and some dimensions of the rotor blade are shown in Fig. 1. The R-2617A profile from the catalogue of pro-

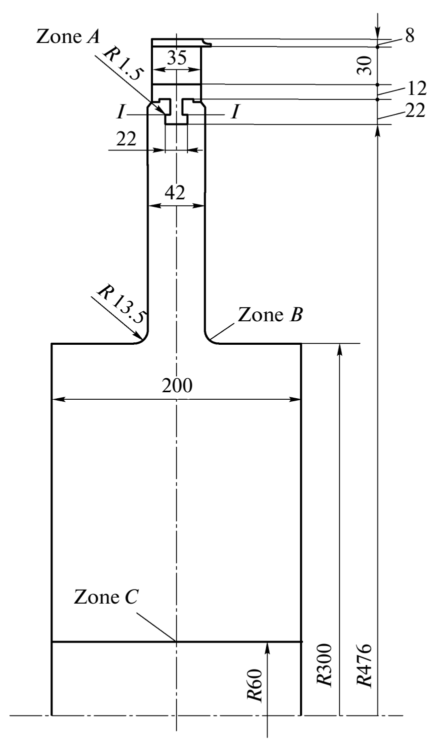

Fig. 1. Fragment of the combined rotor in the HPP first-stage zone.

Table 3. Values of the long-term strength safety margin for the metal of the HIPR fragment in the zone of the HPP first stage

Version	Shaft radius, m	Steam pressure, MPa	Axial force, MN	Long-term strength safety margin $n_{l.t.s}$			
				central channel (zone *C*)		disk fillet (zone *B*)	
				according to the ageing hypothesis	according to the yield hypothesis	according to the ageing hypothesis	according to the yield hypothesis
VD1	0.3	24	2.50	4.23	4.46	1.59	1.75
VD2	0.3	12	1.25	2.67	2.80	1.53	1.65
VD3	0.35	24	2.50	3.01	3.11	1.90	2.06

files developed at the Moscow Power Engineering Institute (MEI) was selected for the rotor blade, and the length of its chord was calculated from the permissible static bending stresses $\sigma^{b}_{\rm perm} \le 35$ MPa.

From the geometrical characteristics of the blade, shroud, and root joint, we calculated the nominal stress in section *I–I* $\bar{\sigma}_{\rm r.n} = 37.54$ MPa (without taking into account the steam pressure equal to 24 MPa).

The following main results were obtained from the calculation.

Elastic stresses at the dangerous point *A*, MPa:

maximal $\bar{\sigma}^{\rm el}_{\varphi} = 262.78$ and

intensity $\sigma^{\rm el}_{*} = 229.47$.

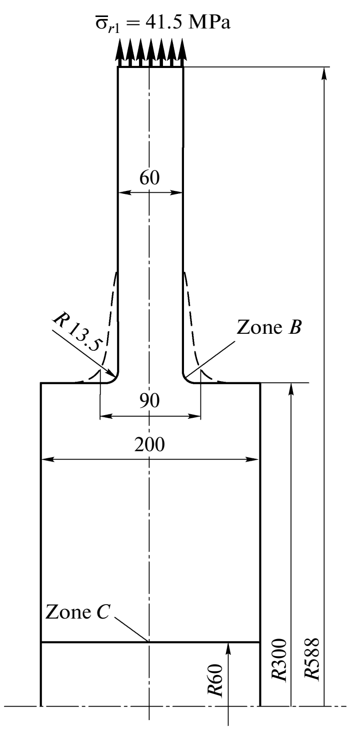

Fig. 2. Fragment of the combined rotor in the IPP first-stage zone.

Stresses in the steady creep state, MPa:

maximal $\bar{\sigma}^{\infty}_{\varphi} = 82.80$,

intensity $\sigma^{\infty}_{*} = 71.73$, and

equivalent maximal stress $\sigma_{\rm eq} = 102.07$.

The long-term safety margin for 200000 h $n_{\rm l.t.s} = 1.57$ (it is necessary to have $n_{\rm l.t.s} \ge 1.3$); therefore, the HIPR in the turbine's high-pressure part satisfies the strength conditions.

The safety margin will be higher if the Japanese steel HR1200 is used. It should also be emphasized that the obtained assessment is conservative, and the actual safety margin is likely to be higher than its calculated value.

Figure 2 shows a sketch of the HIPR fragment in the first-stage zone of the intermediate-pressure part (IPP). This fragment was calculated for long-term strength on the assumption that the metal temperature is equal to 560°C.

The first and the second disks of the IPP must have steam cooling. During operation at rated parameters, the temperature of steam decreases from 580 to 490°C as a result of throttling in the middle seal between the high- and intermediate-pressure parts and reduction of pressure from 24 to 4 MPa. In this case, the rotor metal temperature can be decreased to 560°C. Without cooling, the metal temperature is equal to around 600°C; natural cooling should decrease it by only 40°C, which is quite possible. To obtain the required level of temperature at partial loads, it is necessary to organize additional forced cooling by supplying steam (e.g., from the cold reheat line) to the chamber of the IPP's first stage.

A tentative calculation of the HIPR fragment in the first disk area for long-term strength was carried out for the zones *B* and *C* (see Fig. 2). An assessment of the radial stress at the disk periphery gives $\bar{\sigma}_{r1} = 41.5$ MPa. This value was obtained from the preliminary calculation of the dimensions of the rotor blade used in the IPP's first stage.

The creep characteristics at 560°C are given in Table 2. The long-term strength for 200000 h was determined by recalculating the data for Grade EI993

Table 4. Long-term strength safety margins (according to the yield hypothesis) for the HIPR fragment in the zone of the IPP first stage

Version	Shaft radius, m	Disk thickness at the shaft, m	Long-term strength safety margin $n_{l.t.s}$	
			central channel (zone *C*)	disk fillet (zone *B*)
VD1	0.30	0.06	1.80	1.09
VD2	0.30	0.09	1.55	1.39
VD3	0.35	0.06	1.62	1.19
VD4	0.35	0.09	1.43	1.53

steel and is equal to 210 MPa. Its value for Grade HR1200 steel is noticeably higher and close to 280 MPa. The calculated safety margins obtained for four versions are given in Table 4.

The considered versions differ from one another only in the values of shaft radius and disk thickness at the shaft. The following parameters are the same:

the fragment's metal temperature equal to	560°C
the constants in the creep law	(see Table 2)
the service life equal to	200000 h
the peripheral stresses equal to	41.5 MPa
the long-term strength equal to	210 MPa
the peripheral disk radius equal to	0.588 m
the central channel's radius equal to	0.06 m
the axial size of the shaft fragment equal to	0.2 m
the disk thickness at the periphery equal to	0.06 m
the radial stress concentration ratio in the disk fillet equal to	1.7
the elasticity modulus equal to	1.78×10^5 MPa
the Poisson ratio equal to	0.3
the steam pressure in the chamber before the disk equal to	3.9 MPa
the radial force equal to	2.5 MN.

Calculations for the versions SD1 and SD3 (with the shaft radii equal to 0.30 and 0.35 m) were carried out for a constant disk thickness value at the periphery ($h = 0.06$ m), and for the versions SD2 and SD4 (with the shaft radii equal to 0.30 and 0.35 m), the calculations were carried out at a variable value of this parameter (the hatched lines in Fig. 2). The smallest long-term strength margin relates to the fillet area (zone *B*) for the versions SD1 and SD3 (with constant disk thickness). If the disk has variable thickness (versions SD2 and SD4), the safety margins comply with the adopted standardized values ($n_{l.t.s} \geq 1.3$).

Thus, the steam flowing out from the middle seal with a temperature of around 490°C cools the area of the intermediate-pressure part's first and second disks to the required level of around 560°C. For these disks, it is advisable to use fir-tree blade attachments with rotor blades inserted from the end side instead of a T-shaped root joint. Under these conditions, the HIPR can be made with sufficient long-term strength in the case of using Grade EI993 steel (and the more so if the Japanese steel HR1200 is used).

CONCLUSIONS

(1) The technical characteristics of the proposed K-660-30 steam turbine for the steam parameters 30 MPa and 610/620°C are in line with the formulated design concept:

(i) In its optimal version, the turbine must consist of two cylinders: HIPC + LPC; the HIPC rotor must be made of chromium steel (like Grade EI993 steel) and be furnished with active-type blades for reducing the number of stages, achieving better operational efficiency, and maintaining good efficiency in the period between repairs.

(ii) One double-flow LPC must be made with the last-stage rotor blades having an increased throughput capacity (one flow has a passage area of 16.3 m^2).

(iii) The total number of bearings on the turbine unit is equal to four, and the total number of stages in the turbine is $10 + 8 + 2 \times 4 = 26$.

(2) The HIPC may well be constructed; the HIPR can be made without cooling in the high-pressure part, and the first stages in the IPP can be cooled very easily: by using a throttling leak through the middle seal. The rotor in both the HPP and IPP meets the requirements of long-term strength for the service life equal to 200000 h in the case of using Grade EI993 steel and more so if HR1200 steel is used.

(3) For peripheral seals of the high- and intermediate-pressure flow paths, it is recommended to use variable-pitch multicomb seals, the use of which makes it possible to obtain small peripheral leaks, better integrity during operation, and good repairability.

(4) The efficiency of the turbine unit was determined on the basis of optimistic but quite real efficiencies of turbine compartments. The following technical solutions should be used for achieving these efficiencies:

(i) meridian profiling in the HPP stages;

(ii) saber-shaped nozzle vanes in the IPP and HPP;

(iii) rotor blades without wire braces;

(iv) efficient seals;

(v) high-quality aerodynamic profiling of the stages;

(vi) heating of nozzle vanes in the wet steam region, etc.

In this case, the turbine unit net efficiency may reach $\eta_{TU}^{gr} \approx 51\%$. With the adopted values of boiler efficiency and expenditures for the power station aux-

iliaries and heat transportation, the predicted net electrical efficiency of the power unit $\eta_{el.p.u} \approx 45\%$.

(5) With the formulated design concept implemented, the turbine will have high operational reliability at relatively low capital outlays for manufacturing it.

(6) The following three conditions must be fulfilled for solving the problem of constructing the last stage with a flow pass area of 16–18 m^2: state will, investments, and time. The last condition depends on the first two. With proper organization and sufficient financial support, this work could be accomplished in 3 years.

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